Representation of Turbulent Mixing in the Atmospheric Boundary Layer at Gray Zone Grid Spacings

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With acknowledgement to

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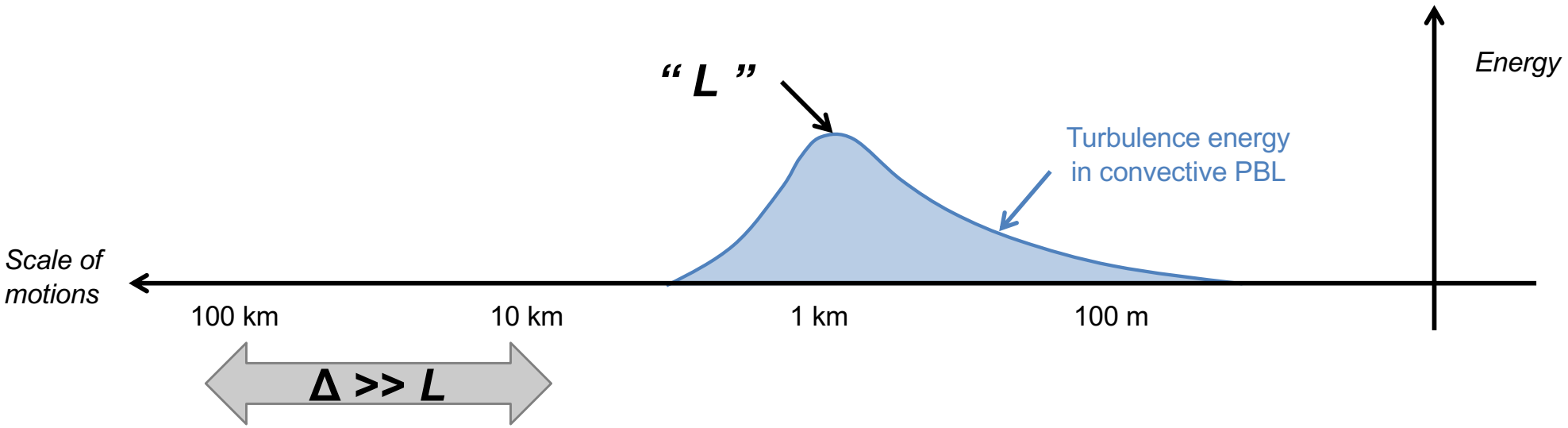
1D PBL parameterization: Δ >> *L*



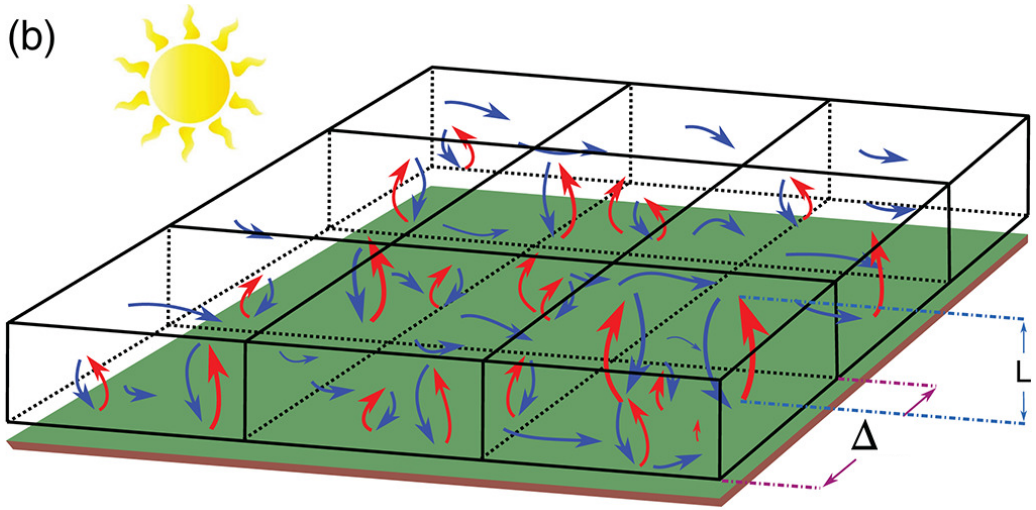
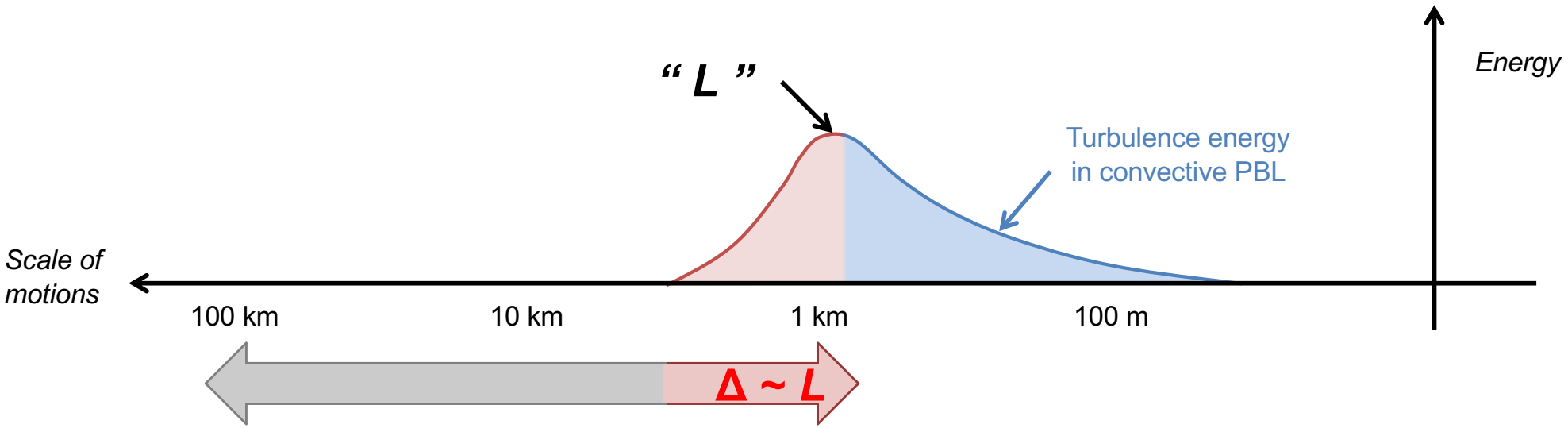
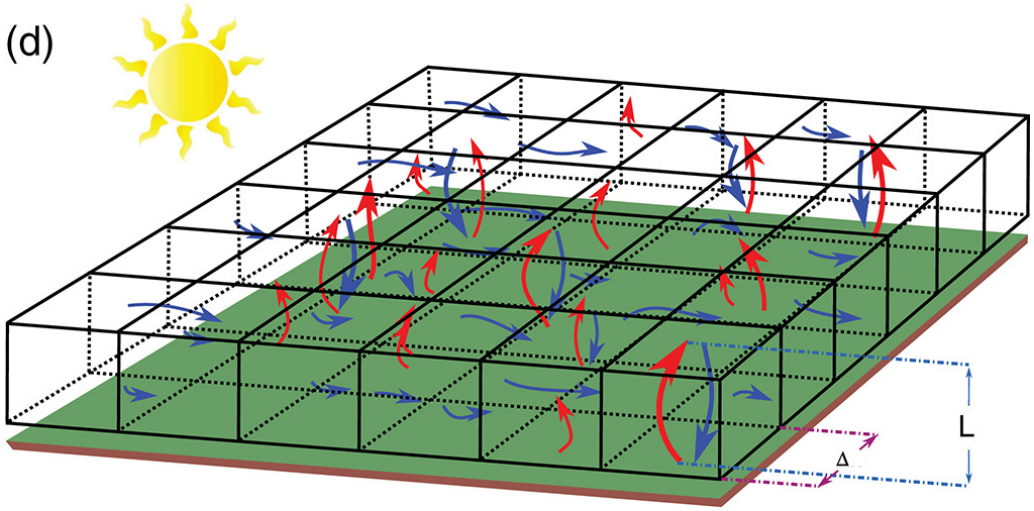


Figure is adopted from ***Kealy (2019, Weather)***.

- All eddies are subgrid-scale.
- *Subgrid-scale* statistics are horizontally homogeneous: *1D vertical transport*.

Gray Zone: Δ ~ *L*





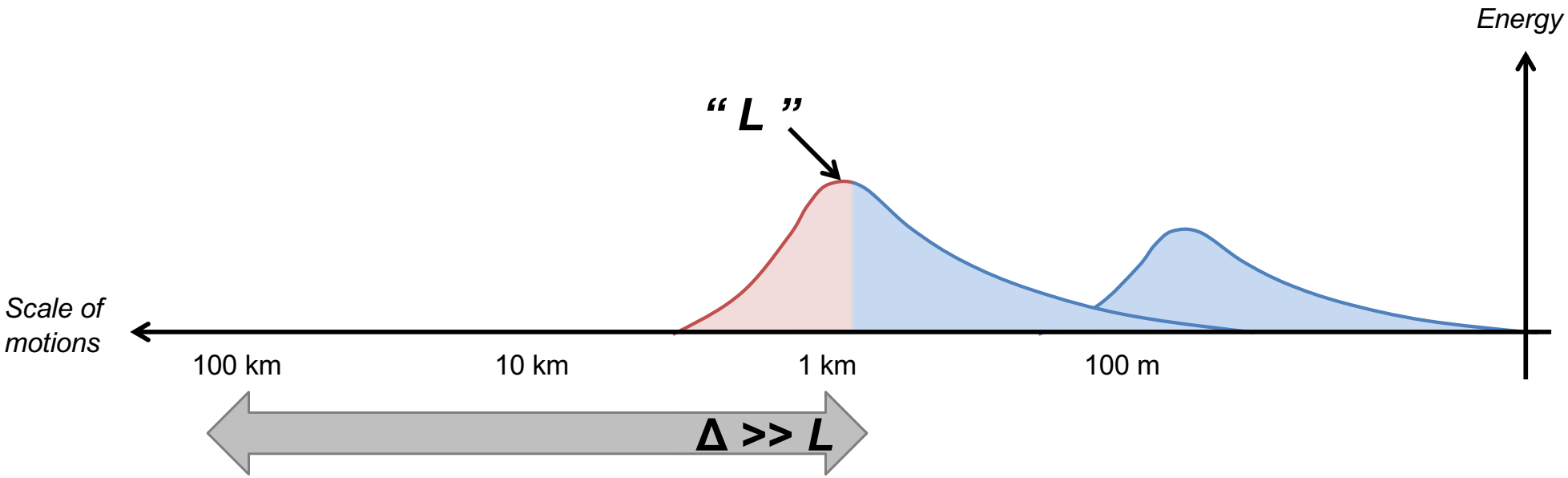
- Large eddies can be *partially resolved*.
- *Subgrid-scale* statistics are horizontally inhomogeneous: *3D transport*.

Figure is adopted from ***Kealy (2019, Weather)***.

$\Delta = O(0.1\text{-}1\ \text{km})$

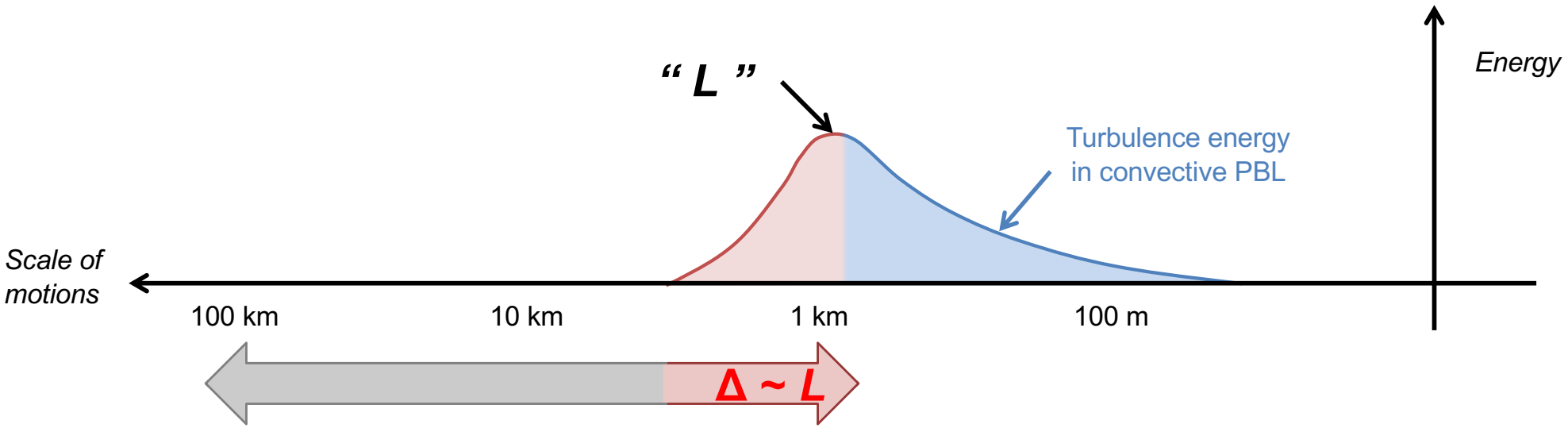
- (model resolution) $\boldsymbol{\Delta \sim L}$ (the peak of energy-containing scales)

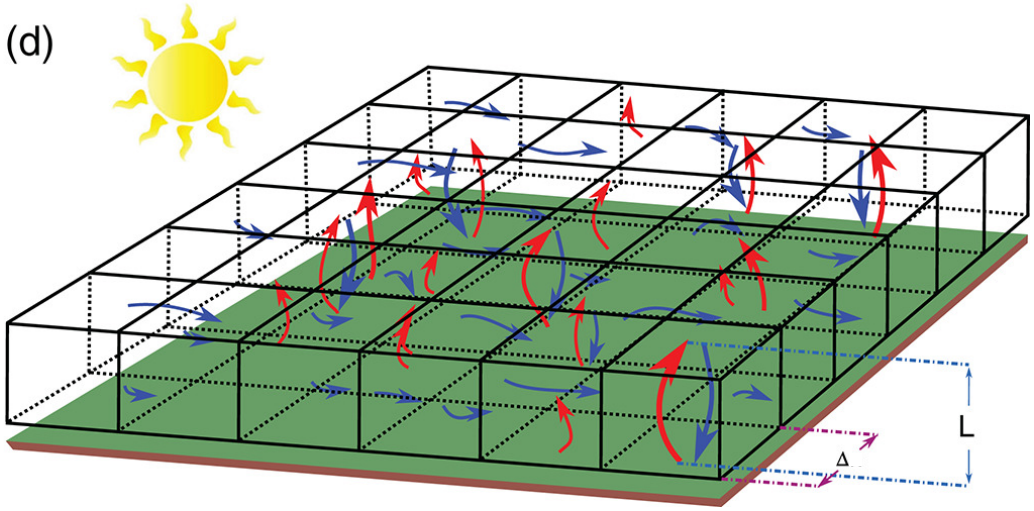
  $\boldsymbol{L \sim z_i}$ (boundary-layer depth)



- The diurnal variations of the ABL: ***L***
  - **O(0.1-1 km)** in the convective ABL
  - Smaller than O(0.1 km) in the stable ABL

Gray Zone: Δ ~ *L*



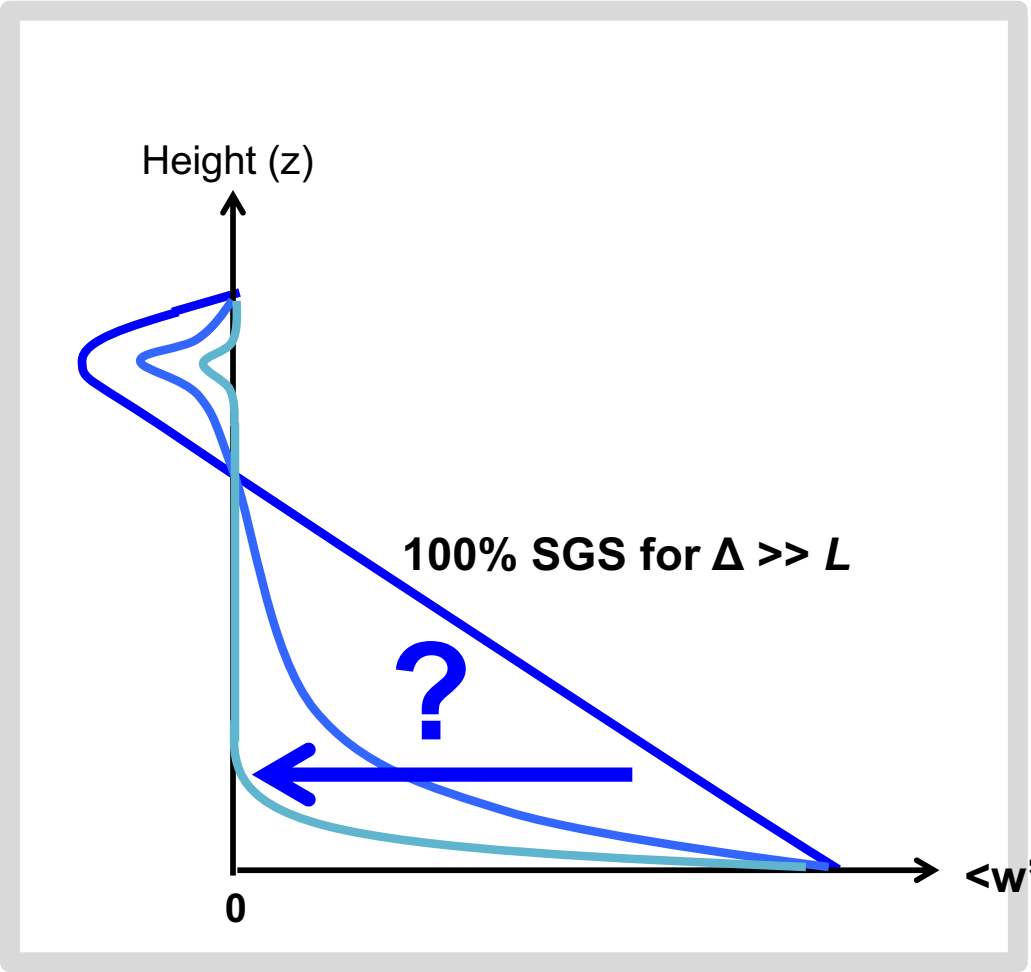


- Large eddies can be *partially resolved*.
- *Subgrid-scale* statistics are horizontally inhomogeneous: *3D transport*.

Figure is adopted from ***Kealy (2019, Weather)***.

Resolution Dependency

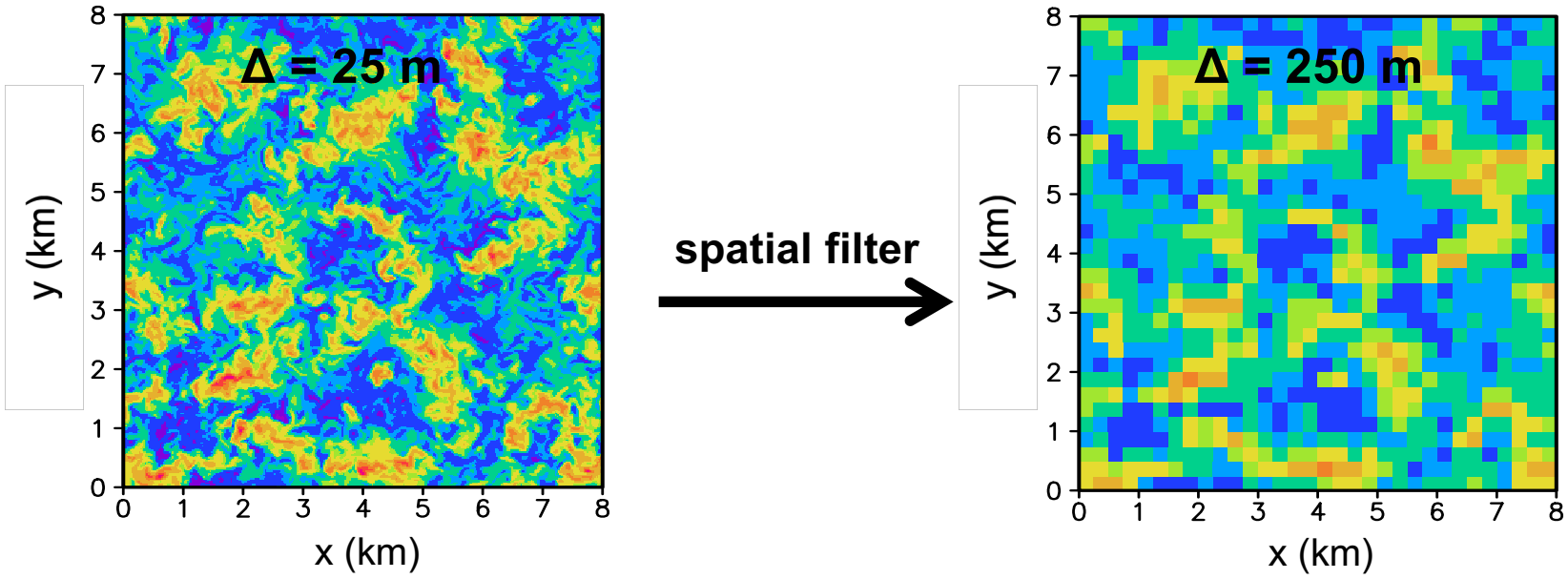
- (an example) Subgrid-scale **Vertical** Heat Transport



Resolution Dependency

- Spatially filtered LES for gray-zone grid spacings

The original method by Honnert et al. (2011, JAS)



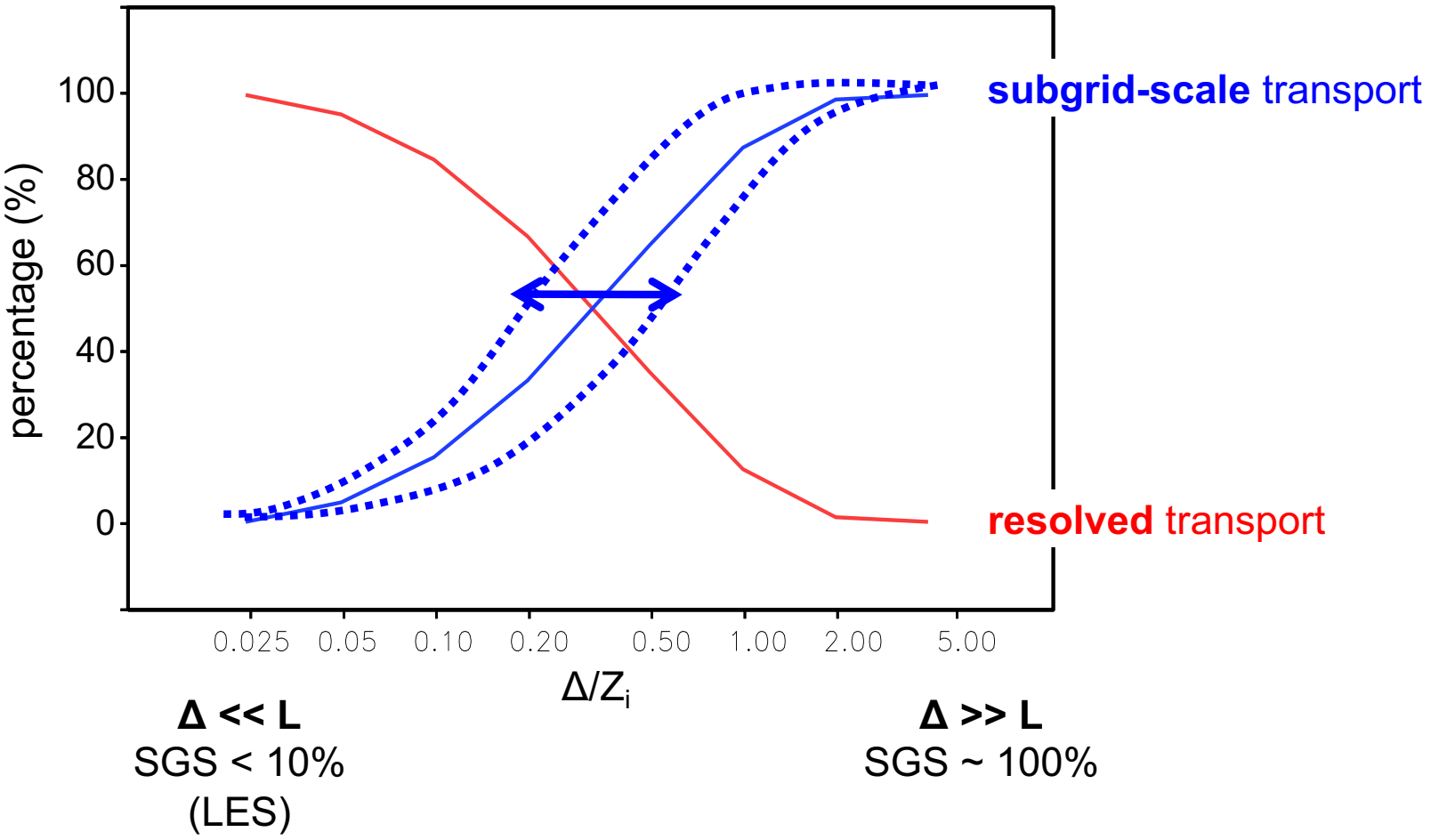
"benchmark" LES fields: W_{LES}

reference "resolved" fields: $\widetilde{W}^{\Delta}$

reference "subgrid-scale" perturbations:

$$w' = W_{LES} - \widetilde{W}^{\Delta}$$

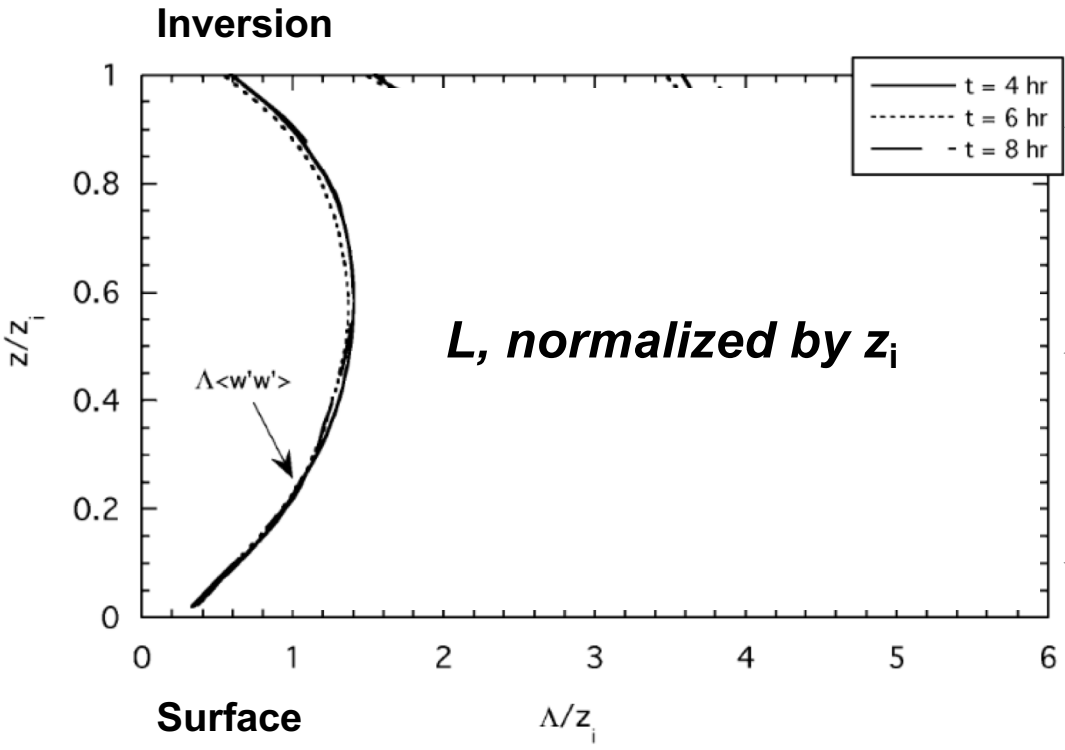
Resolution Dependency



- **Gray zone depends on *L***

L depends on z_i, and..

- Height (Honnert et al. 2011)



***L*, normalized by z_i**

$z = 0.9z_i$

$z = 0.5z_i$

$z = 0.1z_i$

Larger *L*

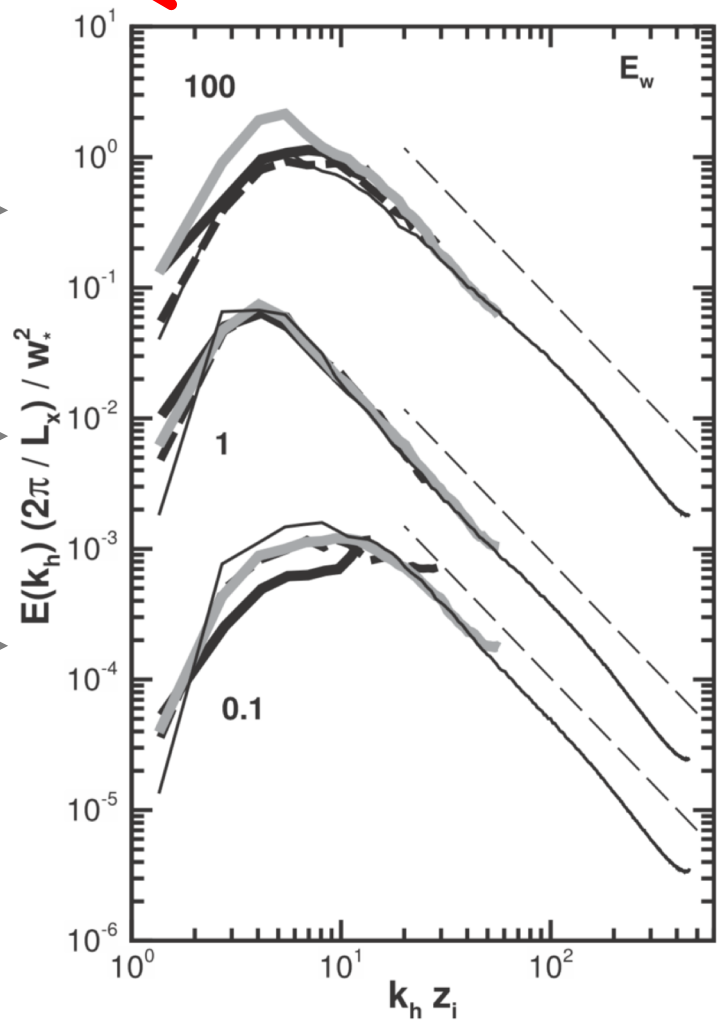


Figure is adopted from ***de Roode et al. (2004, JAS)***.

Figure is adopted from ***Sullivan and Patton (2011, JAS)***.

L depends on z_i, *z*, and..

- Different variables (Honnert et al. 2011)

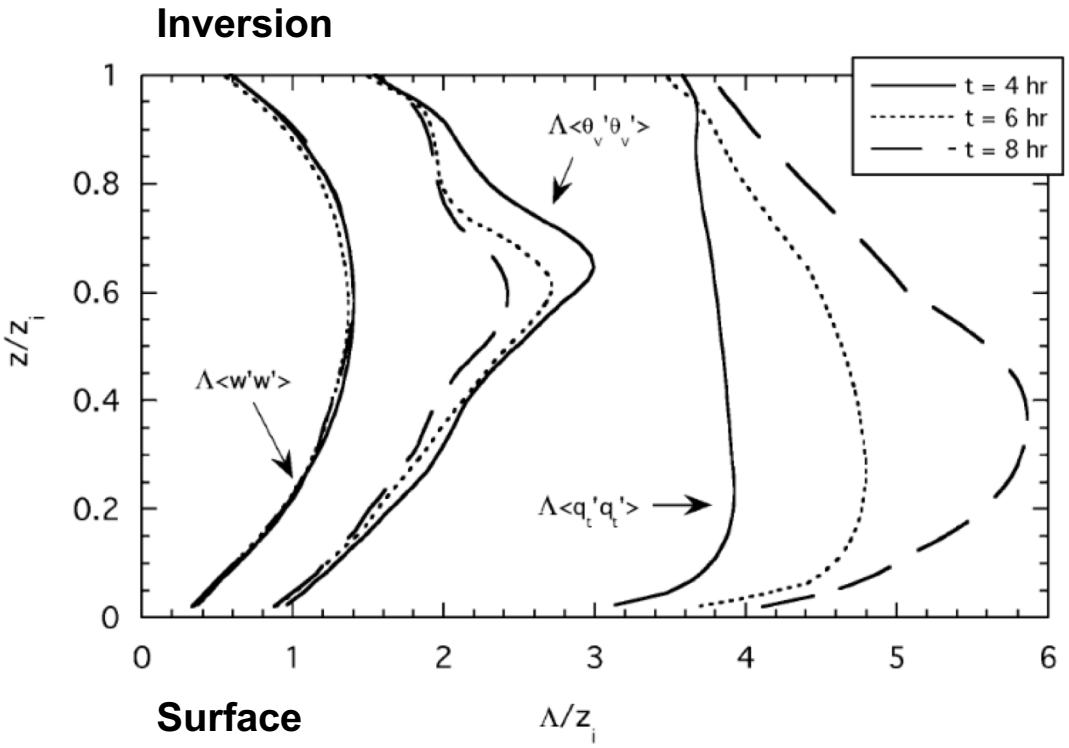


Figure is adopted from
de Roode et al. (2004, JAS).

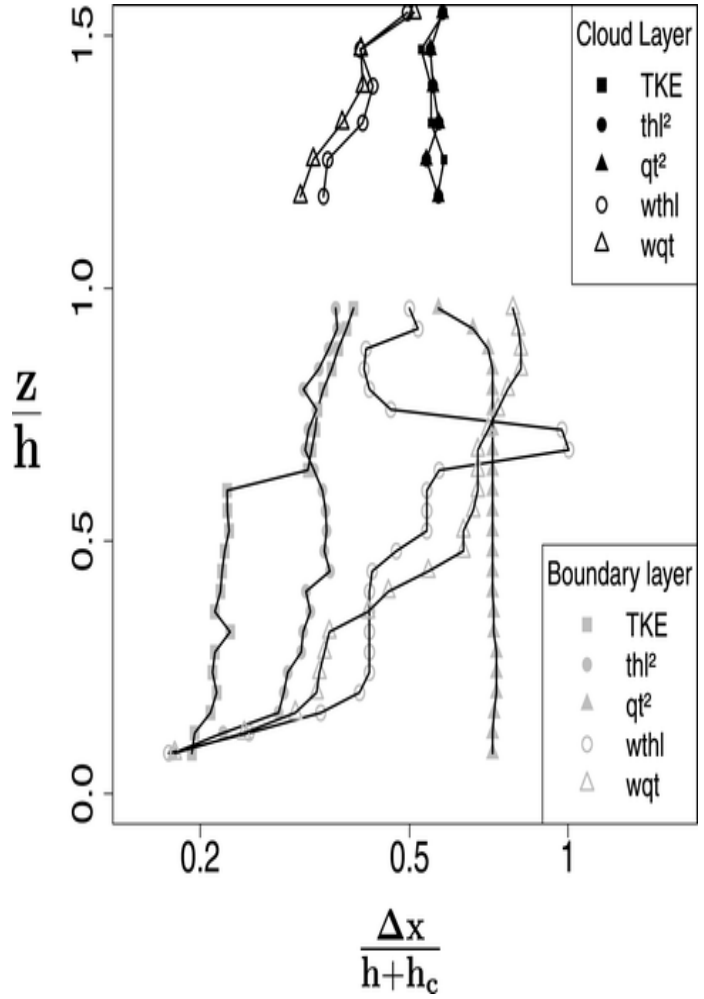


Figure is adopted from
Honnert et al. (2011, JAS).

L depends on z_i, *z*, variables, and..

- ABL Stability (Shin and Hong 2013)

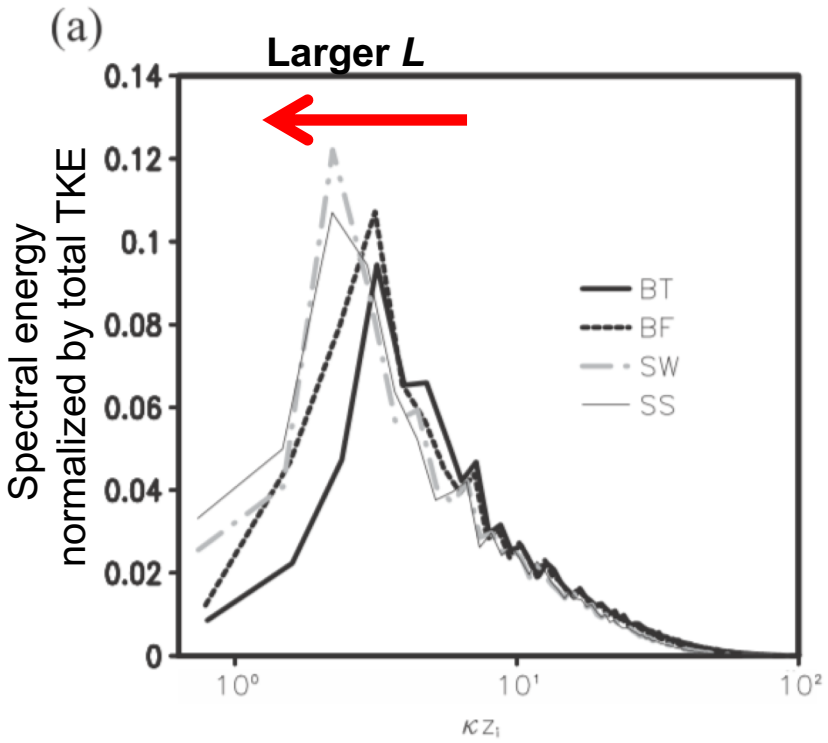
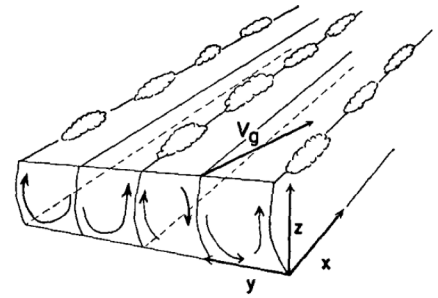


Figure is adopted from ***Shin and Hong (2013, JAS)***.

wind shear increases
surface heating decreases



Horizontal convective rolls

Figure is adopted from ***LeMone (1973, JAS)***.

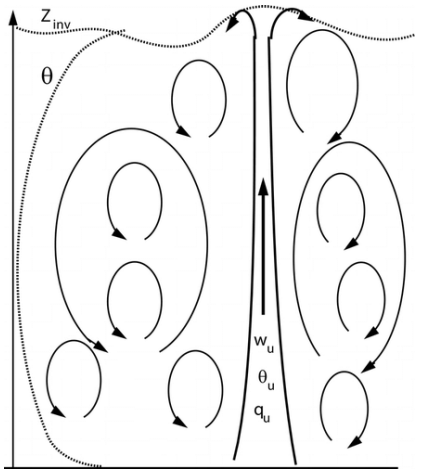
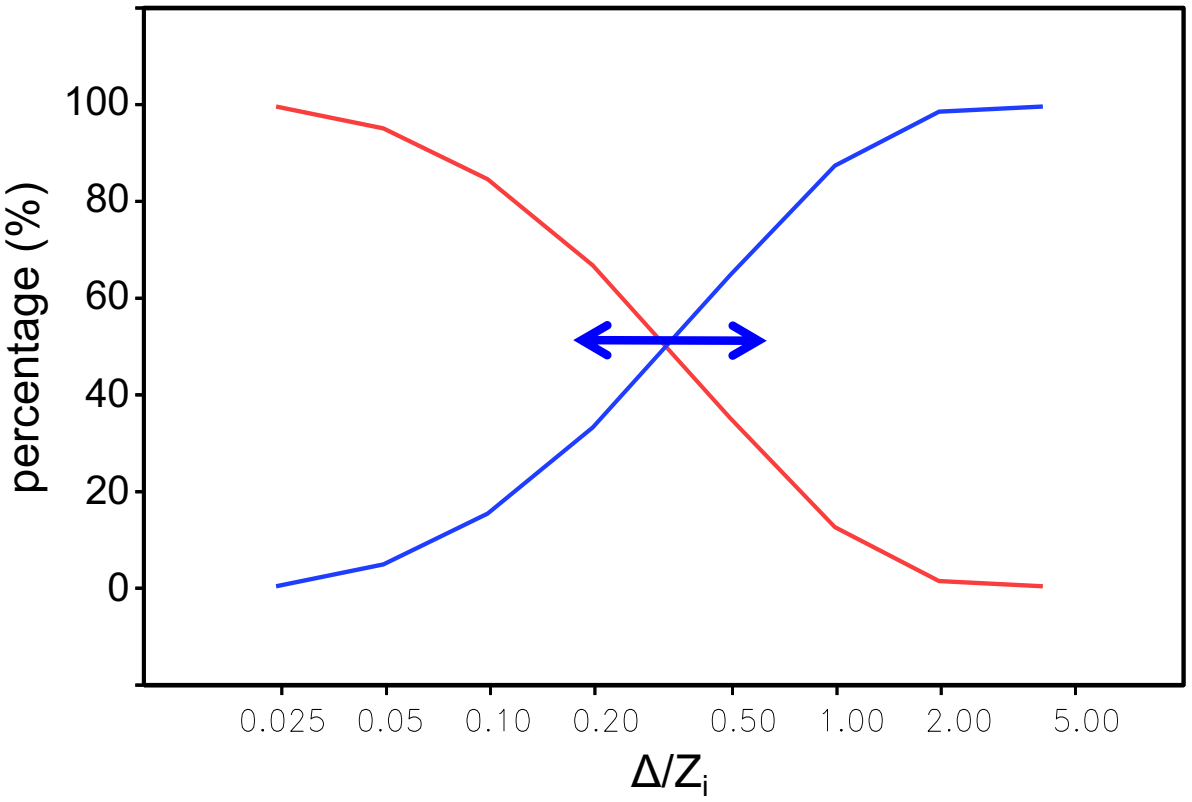


Figure is adopted from ***Siebesma et al. (2007, JAS)***.

Gray Zone and Resolution Dependency

- z_i, z, prognostic variables, and ABL stability



How Various Types of PBL Schemes

Behave on

Scales That Permit Resolved Eddies?

Or

How Resolved Eddies in the Gray Zone

Respond to

Subgrid-Scale Parameterizations?

Shin and Dudhia (2016, MWR)

An idealized, well-constrained, dry CBL case

Case Description

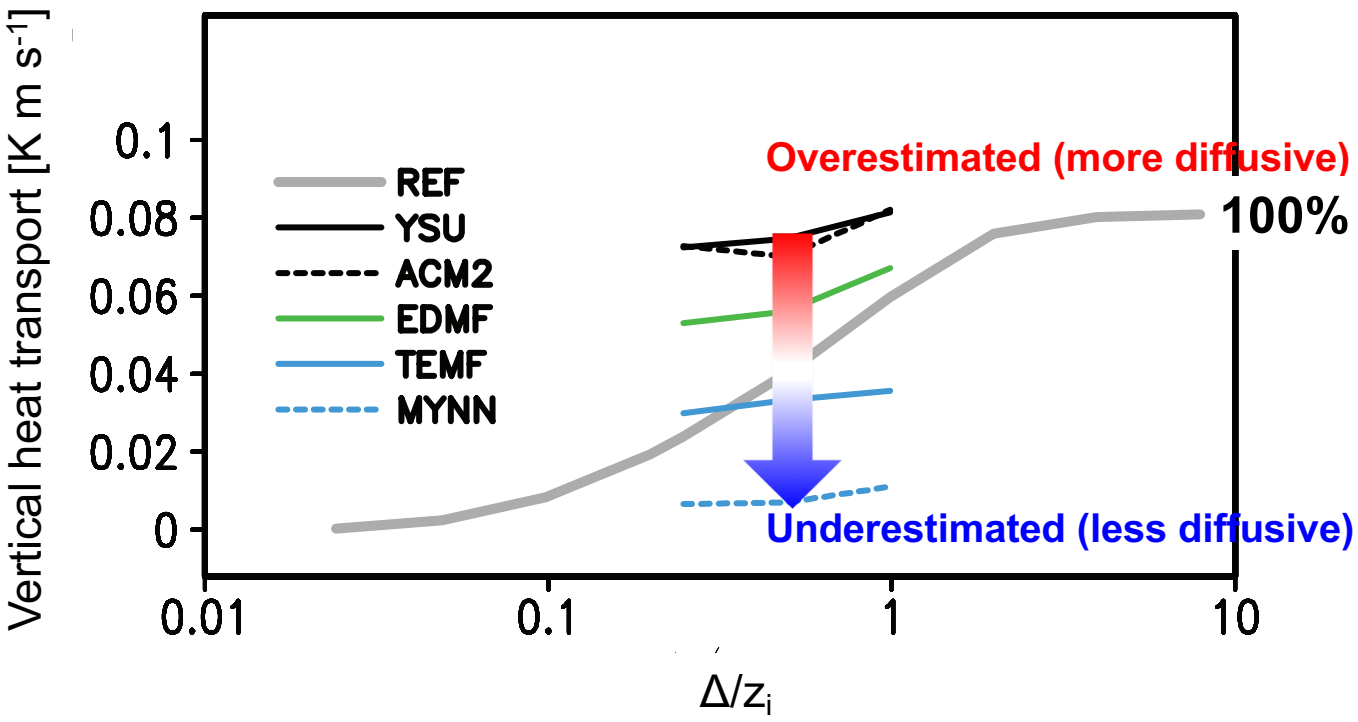
- **no moisture**
- **a constant & homogeneous surface heat flux**: 0.2 K m s^{-1}
- U_g = 10 m s^{-1}
- **no horizontal convective rolls**

Simulation Setup

	Subgrid-Scale vertical transport	Subgrid-Scale horizontal transport	Grid spacing (m)	No. of grids	Domain size (km^2)
LES	3D TKE	3D TKE	25	320^2	8^2
Reference	Filtered from the LES		250, 500, 1000	32^2, 16^2, 8^2	8^2
Simulations	**5 PBL schemes in the WRF model**	3D TKE	**250, 500, 1000**	32^2	8^2, 16^2, 32^2

Resolution Dependency

"Parameterized" vertical transport <w'θ'>



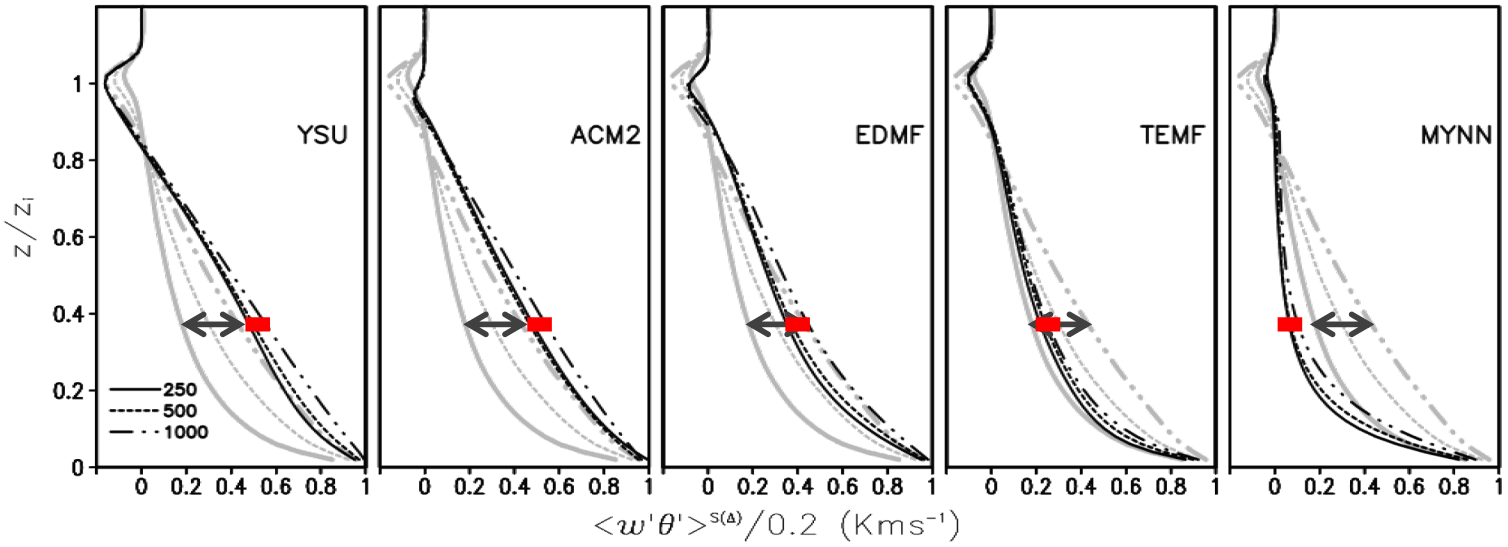
None of them are scale aware.

Resolution Dependency

“Parameterized” vertical transport <w’θ’>

GRAY: reference

BLACK: simulations

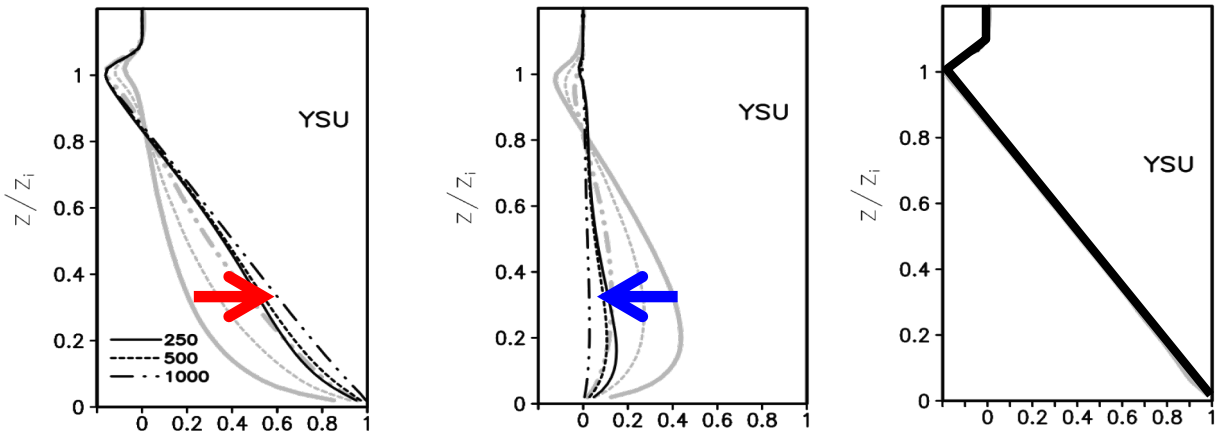


Response of Resolved Motions

YSU

SGS heat transport is overestimated.

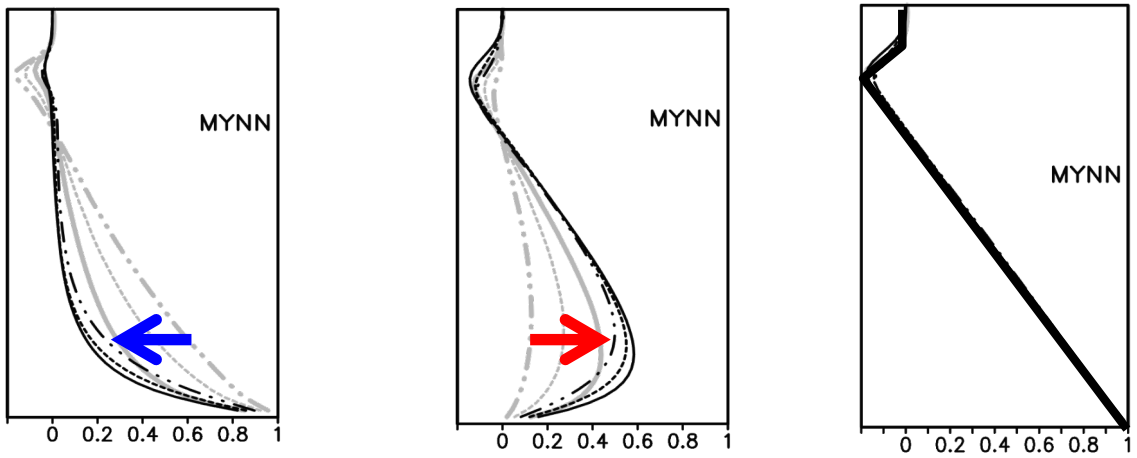
➔Resolved θ' and w' are underestimated.



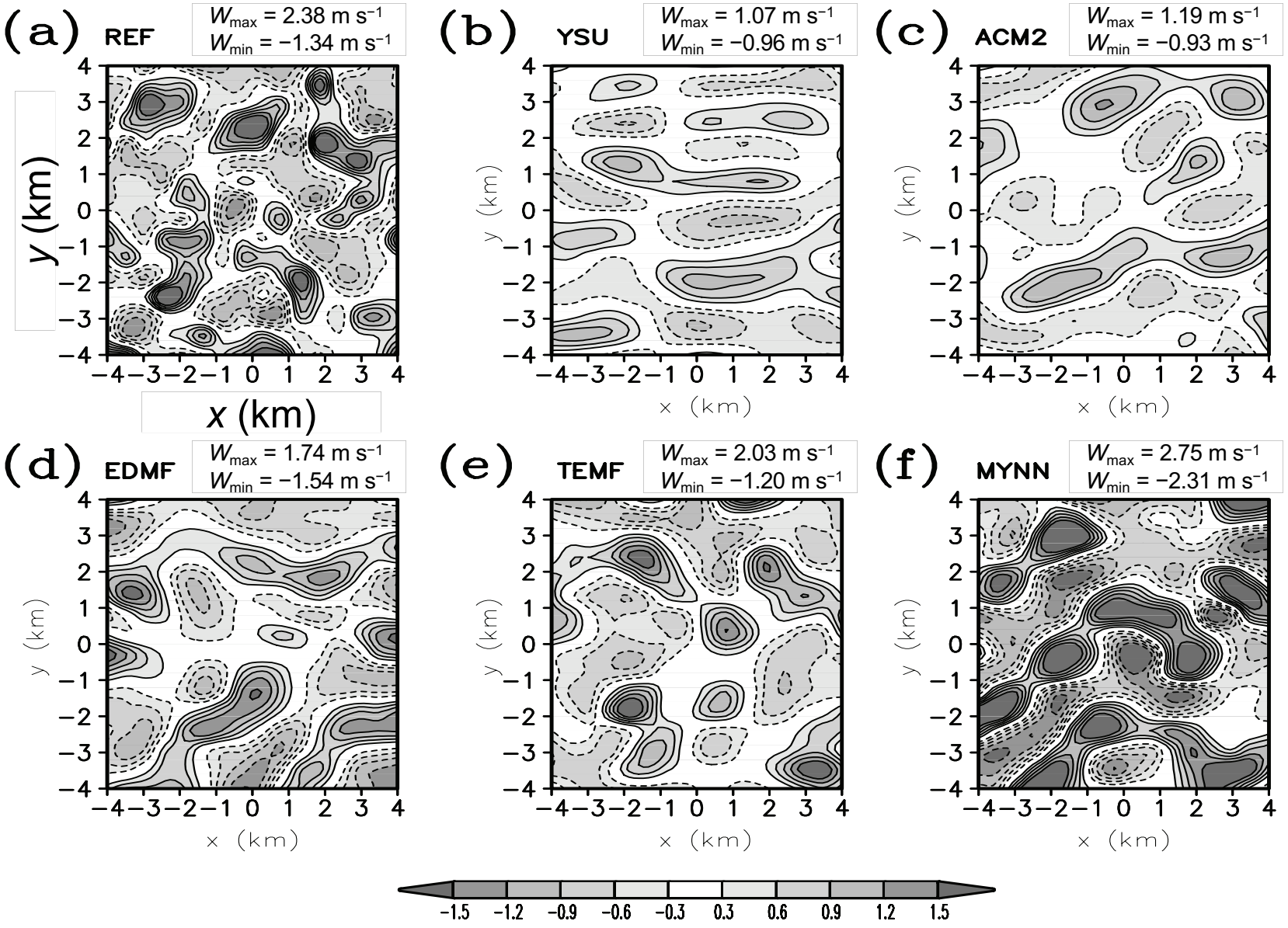
MYNN

SGS heat transport is underestimated.

➔Resolved θ' and w' are overestimated.



Resolved vertical velocity at $0.5z_i$



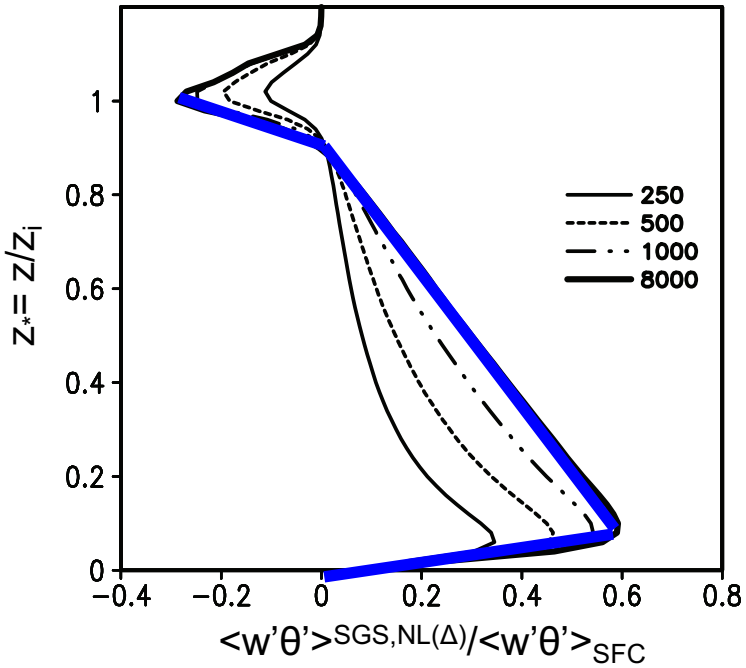
Test a Simple Parameterization: Prescribed Profiles with Explicit Resolution Dependency Functions

Shin and Hong (2015, MWR)

- **WRF PBL option = 11**
- **Convective PBL:** Explicit grid-size dependency
- **Stable PBL:** Same as in the YSU PBL (Hong 2010, QJRMS)
- **Free Atmosphere:** Same as in the YSU PBL (Hong et al. 2006, MWR)

(1) Prescribed non-local heat transport

Role of Large Eddies (from LES)

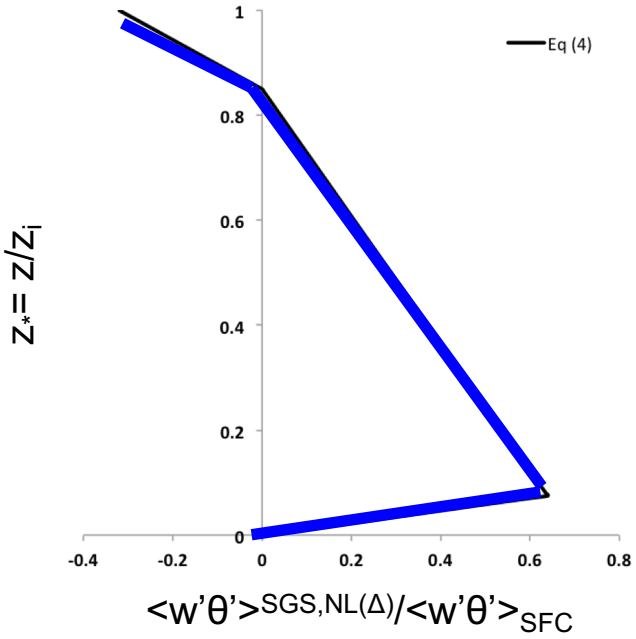


$$\frac{\partial \bar{\theta}}{\partial t} = \cdots - \frac{\partial \overline{w'\theta'}}{\partial z} > 0$$

$$\frac{\partial \bar{\theta}}{\partial t} = \cdots - \frac{\partial \overline{w'\theta'}}{\partial z} > 0$$

$$\frac{\partial \bar{\theta}}{\partial t} = \cdots - \frac{\partial \overline{w'\theta'}}{\partial z} < 0$$

Parameterization

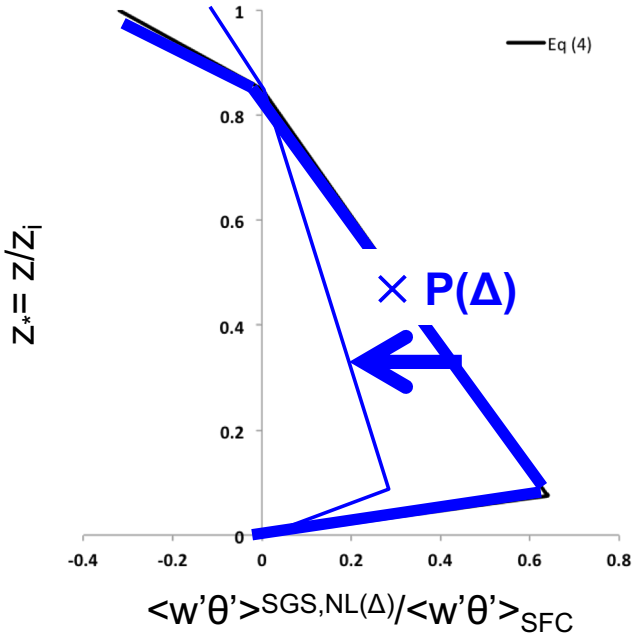


Simplified

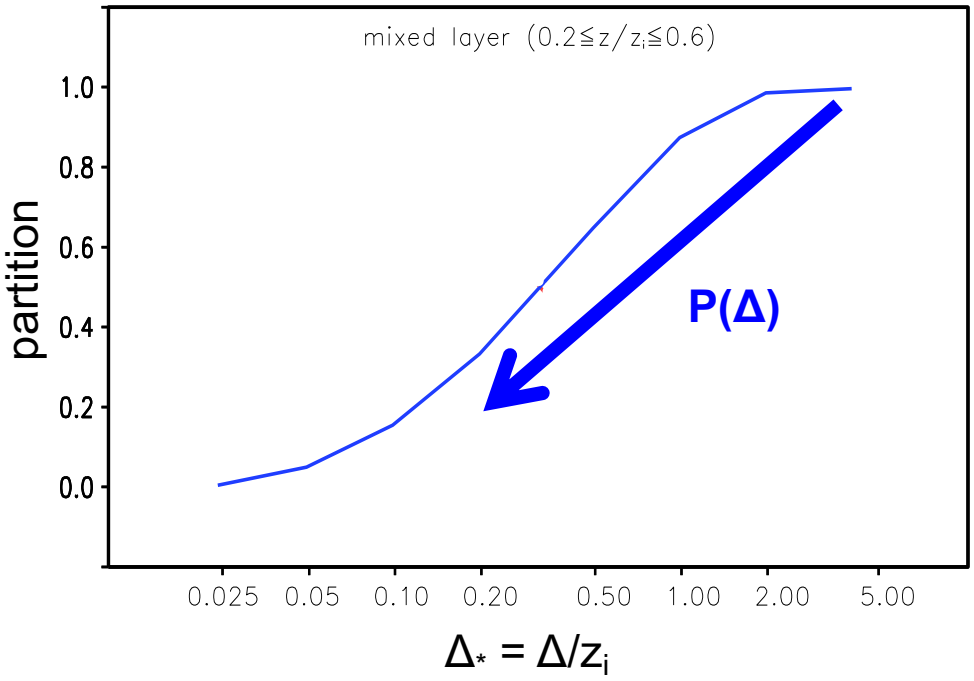
surface-layer cooling, mixed-layer heating, entrainment

(2) Prescribed resolution dependency

Parameterization
Role of Large Eddies

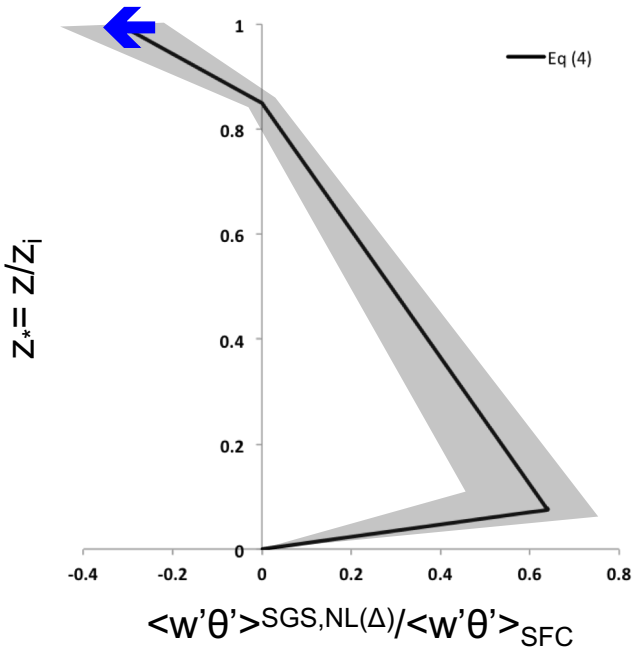


Resolution dependency function
P(Δ*)

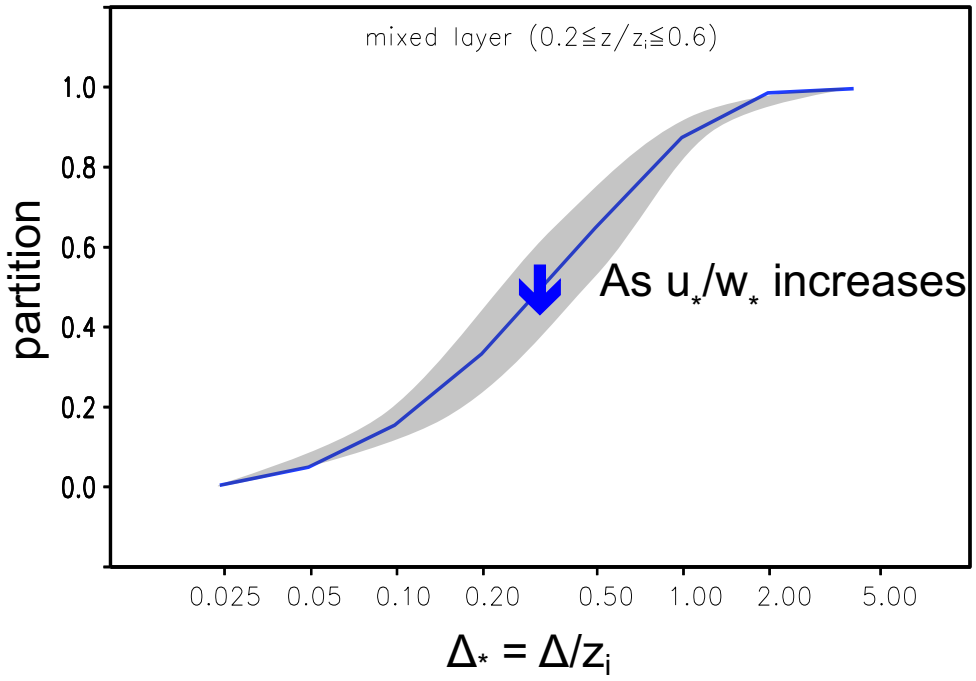


(3) z, Variable, and Atmospheric Stability

Nonlocal transport profile



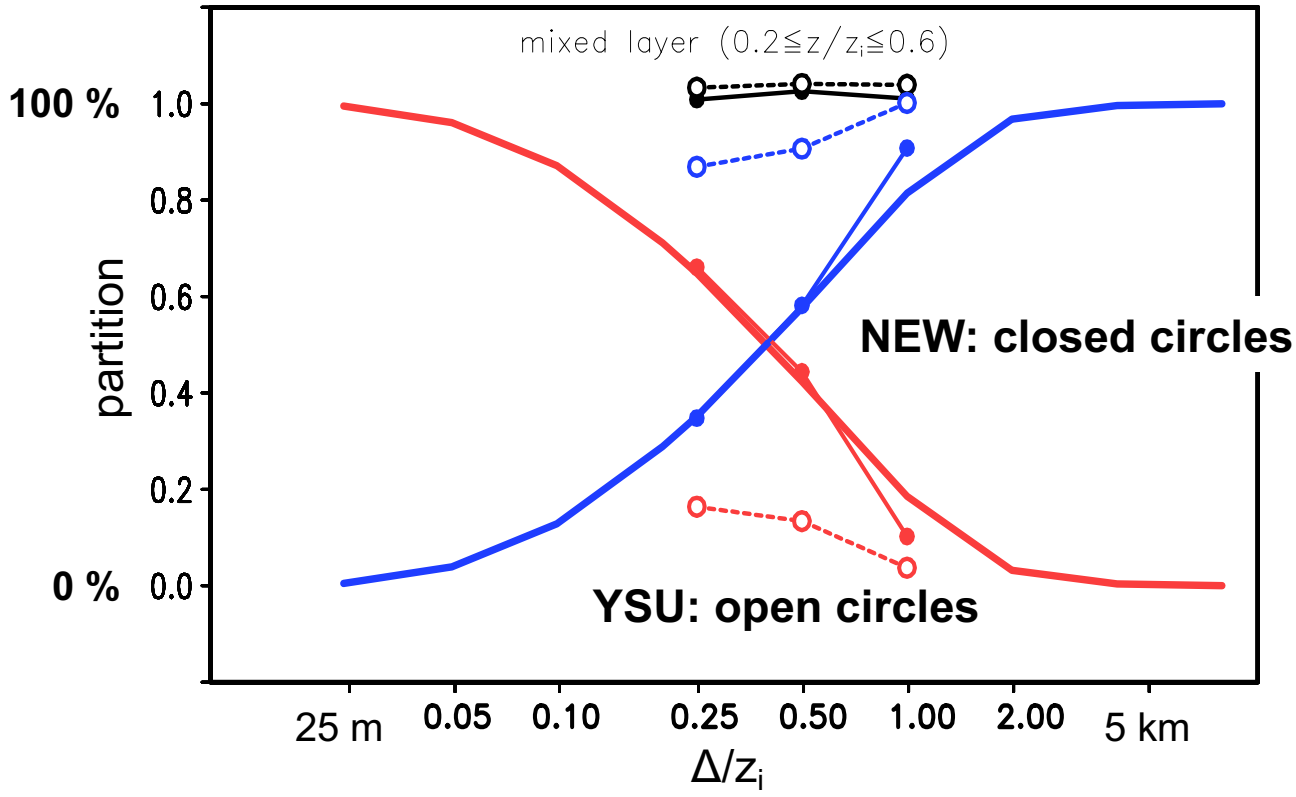
Resolution dependency function
$P(\Delta_*) \rightarrow P(\Delta_*/C_{roll})$



Resolution Dependency

Vertical heat transport <w'θ'>

in mixed layer



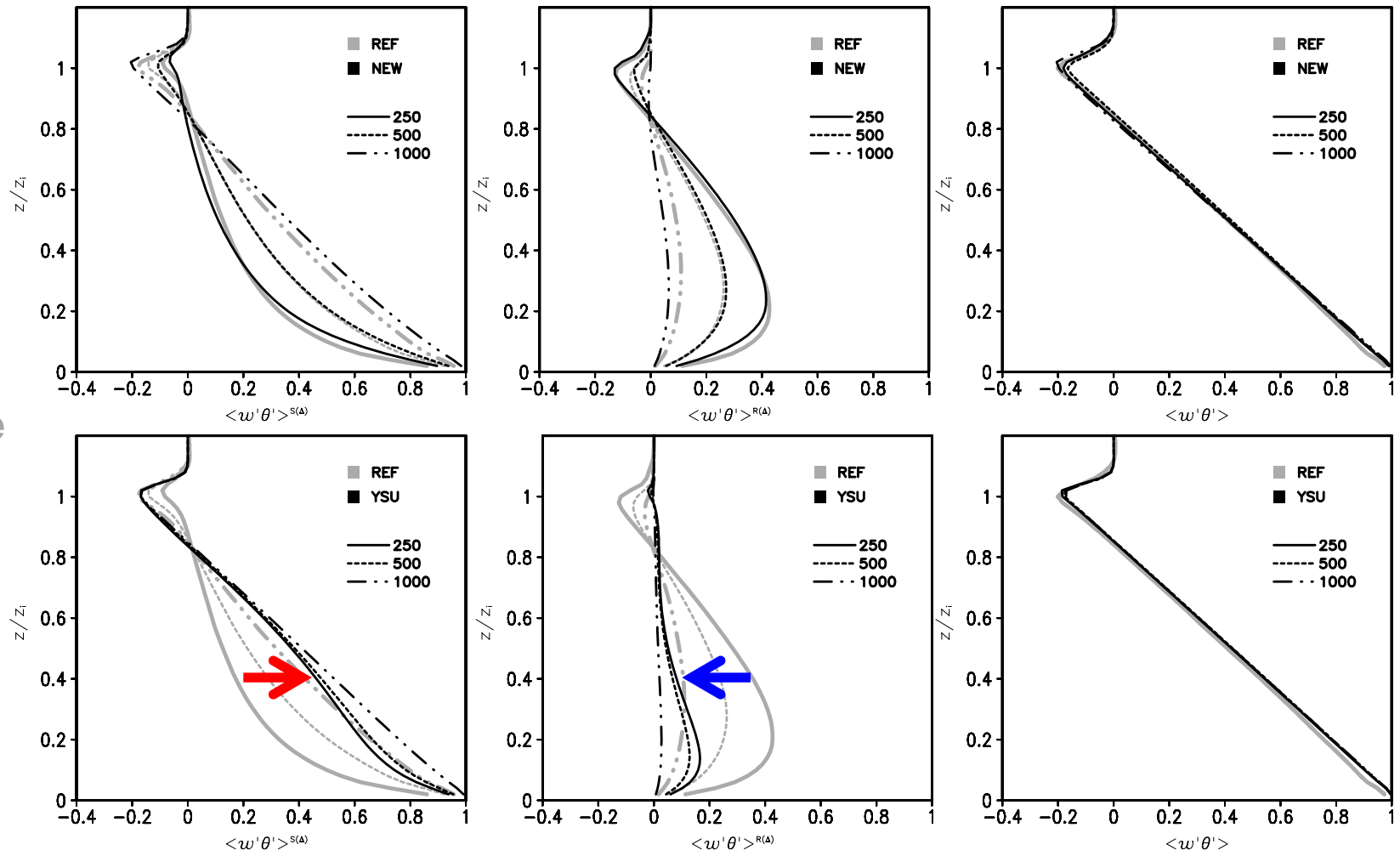
Vertical Profiles of Heat Transport

SGS + Resolved = Total

NEW

GRAY: Reference

YSU

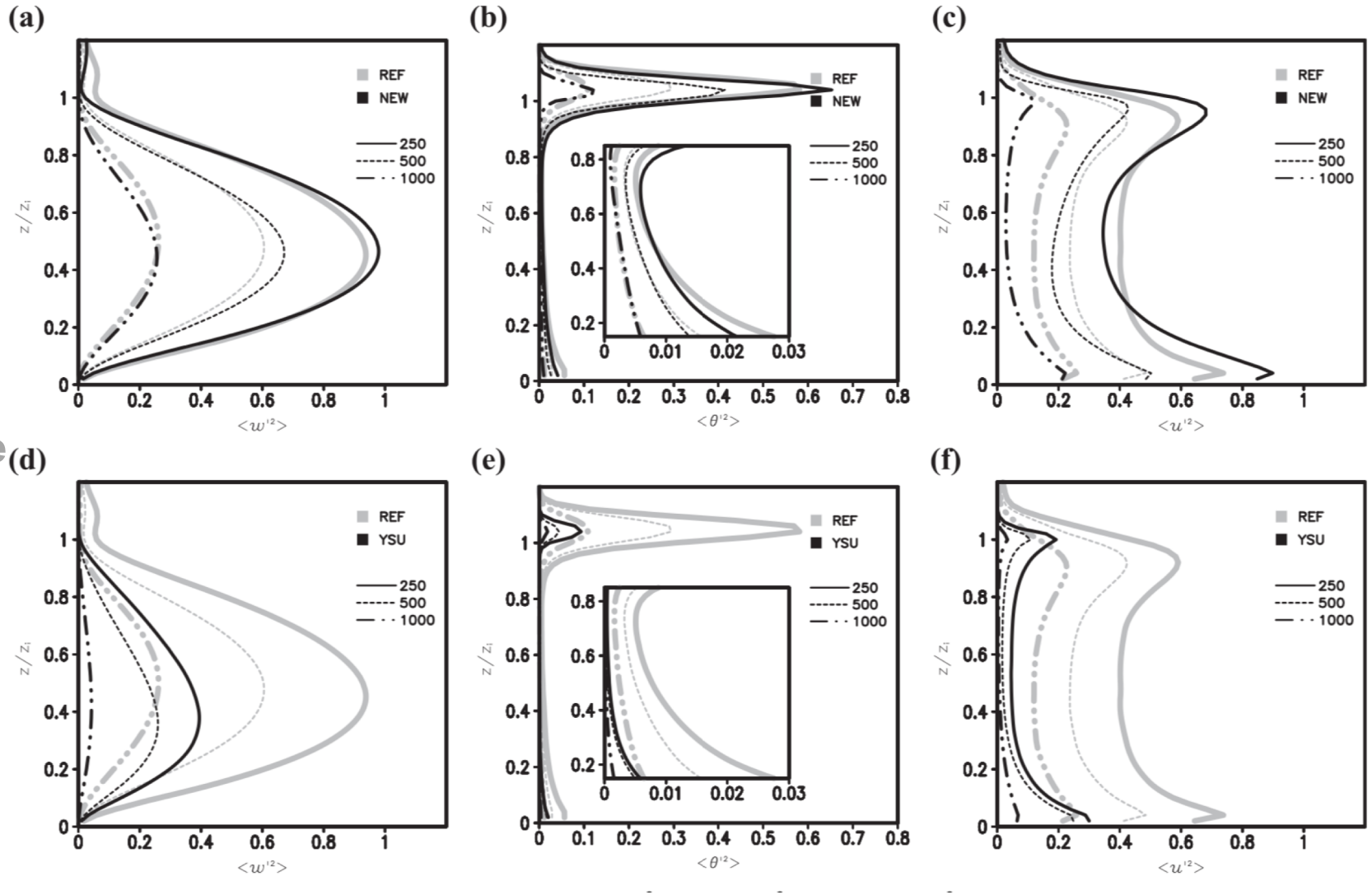


Vertical Profiles of Resolved Variances

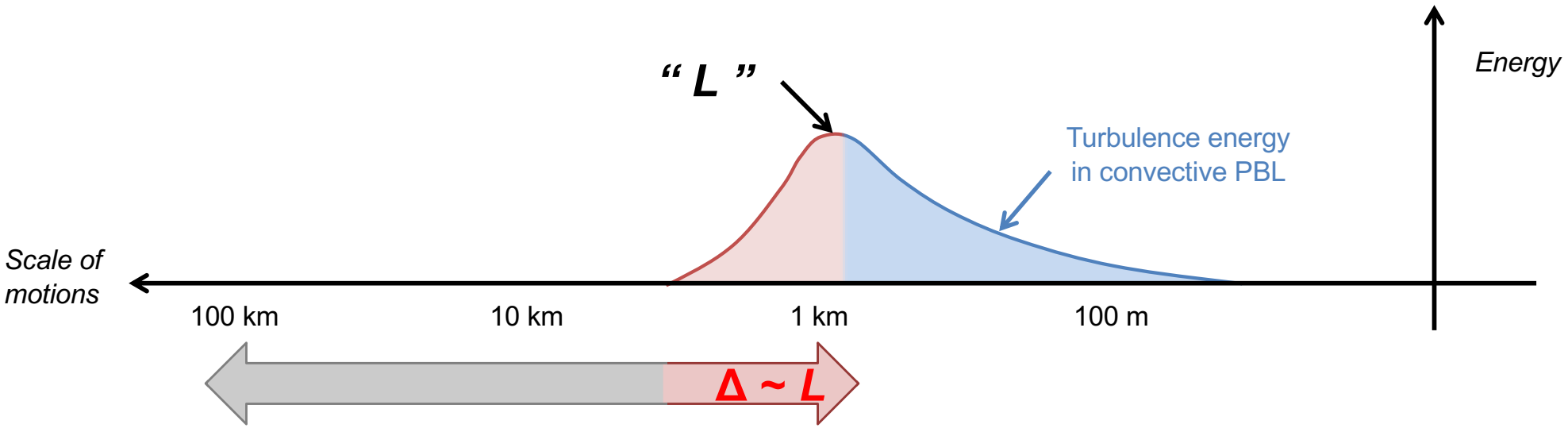
NEW

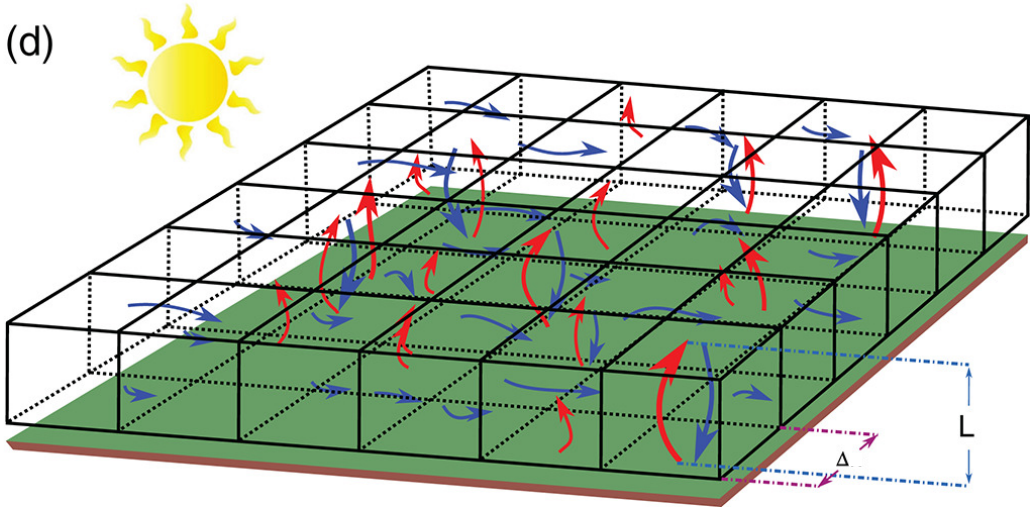
GRAY: Reference

YSU



Gray Zone: Δ ~ *L*





- Large eddies can be *partially resolved*.
- *Subgrid-scale* statistics are horizontally inhomogeneous: *3D transport*.

Figure is adopted from ***Kealy (2019, Weather)***.

Additional Remarks: Recent Developments with WRF

- 1D, but more sophisticated scale-aware representations
  - Olson et al. (2019, BAMS): A scale-aware representation of the mass flux formulation in the MYNN-EDMF scheme
- 3D PBL parameterizations
  - Zhang et al. (2018, MWR)
  - Kosović et al. (2020, J. Phys. Conf. Ser.)